

# OPERATIONAL AMPLIFIER WITH INCREASED COMMON MODE INPUT RANGE

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## CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. Patent Application No. 10/373,576, filed on February 26, 2003, which claims priority to U.S. Provisional Patent Application No. 60/360,179, filed on March 1, 2002, entitled "OPERATIONAL AMPLIFIER WITH INCREASED COMMON MODE USING THREE STAGES AND A SQUEEZABLE TAIL CURRENT SOURCE," which are both incorporated by reference herein.

## BACKGROUND OF THE INVENTION

### Field of the Invention

[0002] The present invention relates to operational amplifiers, and more particularly, to operational amplifiers with increased common mode input range.

### Related Art

[0003] Standard NTSC color video systems have been commonplace since 1970 and continue to be used widely today. The baseband NTSC video signal is an analog signal with an amplitude of approximately 1.3 Volt-peak-to-peak ( $V_{pp}$ ) and has remained largely unchanged since the technology's inception. Early video systems had relatively large supply voltages where the difference in the positive and negative supply voltage would often be 30 volts. Processing a 1.3  $V_{pp}$  signal using analog circuits with 30 V across the supplies means that issues of headroom were rarely a problem. Problems with headroom occur when the input voltage comes too close to the circuit's power supply voltages such that the circuits cannot operate properly. Given a specific supply voltage, a common-mode input range (CMIR) is defined as the range of input voltages over which the circuit can operate correctly.

[0004] The desire to integrate many circuits, both analog and digital, onto a single IC means using CMOS technologies with very small geometries. As transistor sizes shrink, more circuits can be integrated using the same amount of silicon area. However, as the transistor size shrinks, so does the maximum voltage across which the devices can safely operate. As the supply voltage approaches the signal amplitude, the challenges in circuit design increase dramatically. The required CMIR may include much of the available supply voltage. Attenuation of the NTSC signal is usually undesirable, because the NTSC signal is single-ended, and such an attenuation will result in a serious noise problem.

[0005] Many operational amplifiers (op amps) use rail-to-rail circuit techniques which allows the CMIR to include the entire supply voltage. These topologies often employ two input stages, one for operation near each supply voltage. One input stage will use a PMOS differential pair and the other will use a NMOS differential pair. Because the transconductances of these two input pairs are not matched and will not track each other over process variations, the linearity of the overall amplifier is degraded, and high performance is difficult to achieve.

[0006] Another op amp topology often chosen for its high CMIR is the folded-cascode topology (See “Analysis and Design of Analog Integrated Circuits”, Gray, Hurst, Lewis & Meyer, John Wiley and Sons, 4<sup>th</sup> ed. 2001, pp. 446-450). Defining the MOS threshold voltage as  $V_t$  and the overdrive voltage  $V_{GT} = V_{GS} - V_t$ , in Figure 6.28 of Gray *et al.*, maximum input common-mode voltage  $V_{CMI(max)} = V_{DD} - V_{t5} - V_{GT5} - V_{GT1}$  (assume matched transistor pairs **M1-M2**, **M11-M12**, **M1A-M2A** in Figure 6.28 of Grey *et al.*, with the numeric subscript referring to the transistor number). Also the  $V_t$ 's and  $V_{GT}$ 's are assumed to be positive whether the transistor is NMOS or PMOS. Voltages greater than  $V_{CMI(max)}$  will cause **M5** to leave saturation and its current will drop. The folded-cascode circuit often allows the  $V_{CMI}$  to reach the negative supply, usually ground in low supply voltage circuits, without any problems. However, in unity gain buffer configurations, where the inverting

op amp input is tied to the output, it is the output which will limit the voltage swing.

[0007] Although the linearity of the folded-cascode op amp is better than the typical rail-to-rail designs, it still has linearity problems due to the finite output impedance of **M5** in Figure 6.28 of Gray *et al.* As the common mode input voltage  $V_{\text{CMI}}$  changes, the tail current  $I_{\text{D5}}$  will change, which will in turn change the gain of the stage. The stage gain varies as a function of the input stage transconductance  $g_m$  times the output resistance  $R_0$ . The gain goes down as the tail current increases. To overcome this problem, the tail current source could be cascoded, however this would further reduce  $V_{\text{CMI(max)}}$  by an additional  $V_{\text{GT}}$  term.

#### BRIEF SUMMARY OF THE INVENTION

[0008] Accordingly, the present invention is directed to an operational amplifier with increased common mode input range that substantially obviates, one or more of the disadvantages of the related art.

[0009] There is provided an operational amplifier including a first stage with a first differential transistor pair receiving a differential input signal at their gates, a first tail current source transistor connected to sources of the first differential transistor pair, and a load transistor pair connected in series with drains of the first differential transistor pair. An input stage includes a second differential transistor pair connected to respective drains of the first differential transistor pair at their gates, and a second tail current transistor connected to sources of the differential transistor pair. An output stage outputs a signal corresponding to the differential input signal.

[0010] In another aspect there is provided an operational amplifier including a first stage inputting a differential input signal. An input stage includes a second differential transistor pair connected to the first stage, and a tail current transistor connected to sources of the differential transistor pair. An output stage outputs a signal corresponding to the differential input signal. The first stage expands a common mode input range of the input stage.

[0011] Additional features and advantages of the invention will be set forth in the description which follows, and in part will be apparent from the description, or may be learned by practice of the invention. The advantages of the invention will be realized and attained by the structure particularly pointed out in the written description and claims hereof as well as the appended drawings.

[0012] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory and are intended to provide further explanation of the invention as claimed.

#### BRIEF DESCRIPTION OF THE DRAWINGS/FIGURES

[0013] The accompanying drawings, which are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and together with the description serve to explain the principles of the invention. In the drawings:

[0014] **FIG. 1** illustrates a three-stage operational amplifier of one embodiment of the present invention;

[0015] **FIG. 2** illustrates an operational amplifier input stage biased by a squeezable tail current source of one embodiment of the present invention;

[0016] **FIG. 3** illustrates a higher level schematic of the closed loop operational amplifier of **FIGs. 1** and **2**; and

[0017] **FIG. 4** illustrates a graph showing improvement in common mode input range using the present invention.

#### DETAILED DESCRIPTION OF THE INVENTION

[0018] Reference will now be made in detail to the preferred embodiments of the present invention, examples of which are illustrated in the accompanying drawings.

[0019] **FIG. 1** illustrates a three-stage amplifier of one embodiment of the present invention. As shown in **FIG. 1**, the amplifier includes a conventional 2-stage amplifier **102**, and an added stage **101** (a “ $g_m$ -  $g_m$  stage”). These stages will be referred to as conventional amplifier **102** and "first stage" **101** when referring to **FIG. 1**.

[0020] The amplifier **102** is well known in the art and includes two differential pair transistors **M4**, **M5**, NMOS transistor pair **M8** and **M9**, a tail current transistor **M13**, and output stage **M12**, **M11** and **M10**, outputting a signal  $V_{OUT}$ . Transistors **M4**, **M5**, **M13**, **M12**, **M11** and **M10** are PMOS transistors, and transistors **M8** and **M9** are NMOS transistors. Sources of transistors **M8** and **M9** are connected to ground. Drain of transistor **M9** is connected to gate of transistor **M10**, and to output  $V_{OUT}$  through capacitor **C0** (2.4 pF) and resistor **R1** (140  $\Omega$ ). Transistors **M4**, **M5**, **M8** and **M9** collectively represent an example of an input stage **102A**, and transistors **M10**, **M11** and **M12** is an example of an output stage **102B**. In other words, amplifier **102** is a conventional 2-stage op amp.

[0021] In one embodiment, bias voltages  $V_{B2}$ ,  $V_{B3}$ ,  $V_{B3C}$  are typically around 1.2-1.4 V. The supply voltage  $V_{DD}$  is typically 2.5 V, but a variation of 10-15% is often seen, therefore, a nominally 2.5V circuit must operate down to 2.2V.

[0022] The gain of conventional amplifier stages varies with output voltage often resulting in distortion and nonlinearity. In practical video applications, it is desirable to have at least 10 bits of linearity, i.e., the circuit should be linear to one out of  $2^{10}$ , which corresponds to about 60 dB of linearity (1 bit = 6 dB). It is more desirable to have at least 70 dB of linearity, which corresponds to 11-12 bits. It is also desirable to design a circuit using plain CMOS technology, and to have a circuit that has low power, low area, low noise, high linearity and high swing. Differential pair transistors **M4** and **M5** cannot accomplish it alone.

[0023] Adding a low-gain, high-bandwidth input stage to amplifier **102** will sacrifice some of its closed loop bandwidth. However it simplifies and improves many of the aspects of the op amp.

[0024] As further shown in **FIG. 1**, first stage **101** includes an input differential transistor pair **M0** and **M1**, whose drains are connected to load transistors **M2** and **M3**, respectively. Drains of transistors **M2** and **M3** are connected to ground, as are their gates. Substrates of transistors **M2** and **M3** are connected to their sources.

[0025] A tail current transistor **M14** has a drain connected to sources of transistors **M0** and **M1** (at node tail1), and its source connected to the supply voltage  $V_{DD}$ . Transistor **M14** has a gate voltage of  $V_{BI}$  (a DC bias voltage), a gate of transistor **M0** is driven by  $V_{IP}$ , and a gate of transistor **M1** is driven by  $V_{IN}$ . In closed loop operation (see **FIG. 3**),  $V_{IN}$  and  $V_{OUT}$  would be connected to each other (not shown in **FIG. 1**).  $V_{IN}$  and  $V_{IP}$  correspond to the "-" and "+" inputs of an op amp (see **FIG. 3**).

[0026] Drains of **M0** and **M1** are also connected to gates of **M4** and **M5**, respectively.

[0027] As the gain of first stage **101** is the ratio of the transconductances of transistors **M0** and **M2**,  $g_{M0}/g_{M2}$ , this gain remains constant over variations in process temperature and bias because all the transistors are PMOS devices. The first stage **101** absorbs all the variation in  $V_{CMI}$ , therefore simplifying the design of amplifier **102** and allowing it to be optimized for high gain and low noise. In typical applications, the closed loop gain of the op amp of **FIG. 1** is approximately 1, i.e., first stage **101** acts as a buffer stage. If the open loop gain of first stage **101** is 1.7, noise at the input is reduced by  $1.7^2$ , i.e., the proposed added stage results in a noise advantage.

[0028] The average voltage at nodes ggn and ggp does not change, i.e., it is fixed despite the swing in the input voltages  $V_{IN}$  and  $V_{IP}$ . First stage **101** rejects the common mode voltage of signals applied at  $V_{IP}$  and  $V_{IN}$ . Thus, wide input swings are absorbed by first stage **101**. When input voltages at the gates of **M0** and **M1** swing towards negative supply, common mode input

voltage into amplifier **102** is still fixed, since variation in the common mode input voltage is absorbed by first stage **101**.

[0029] Note that tail current source transistor **M14** may be replaced with an ideal current source.

[0030] Transistors **M14**, **M0**, **M1**, **M2** and **M3** are PMOS transistors in the circuit shown in **FIG. 1**. If the polarity of all transistors is reversed (i.e. all the NMOS transistors in **FIG. 1** were replaced with PMOS transistors, and all the PMOS transistors were replaced with NMOS transistors), the circuit would work in the same manner. It is important, however, that **M0** and **M1** be of the same polarity (i.e., NMOS or PMOS), and **M2** and **M3** be of the same polarity. If control over manufacturing process parameters were such that threshold voltage, transconductance and body effect (i.e., body-source voltage or substrate-source voltage) were matched perfectly over the operating temperature range (in other words, the small signal model parameters of transistors **M0-M3** were substantially identical), then differential transistor pair **M0** and **M1**, and load transistor pair **M2** and **M3** need not be of the same polarity. However, to the extent the small signal model parameters of the four transistors **M0-M3** are not perfectly matched, transistors **M0-M3** need to be of the same polarity (all PMOS, or all NMOS).

[0031] As shown in **FIG. 1**, the  $V_{CM1(max)}$  of the circuit is similar to the folded cascode, though it does not require a cascoded tail current source for improved linearity resulting in lower power. Here,  $V_{CM1(min)} = V_{t2} + V_{GT2} - V_{t0}$ , (with the numeric subscript referring to the transistor number) which, assuming the  $V_t$ 's are equal, reduces to  $V_{GT2}$ . However, the body effect of MOS transistors will increase  $V_t$  as the bulk-source voltage ( $V_{BS}$ ) increases. This is used to some advantage in this topology. Tying the bulk (substrate) connection to the source of the load transistors **M2**, **M3** means  $V_{BS} = 0$  and  $V_t$  for the load transistors **M2**, **M3** will not increase. Leaving the substrate of the input differential transistor pair **M0**, **M1** tied to the positive supply  $V_{DD}$  means that as  $V_{CM1}$  decreases,  $V_{t0}$  increases and  $V_{CM1(min)}$  is reduced, increasing the effective CMIR.

[0032] Due to the substrate-to-source connections of load transistors **M2** and **M3**, the amplifier circuit gets an additional 100 millivolts of extra swing.

[0033] **FIG. 2** illustrates a modification of the amplifier of **FIG. 1**, including the addition of a current source **103** (amplifier **102** is not shown for clarity). When  $V_{IP}$  and  $V_{IN}$  swing towards the  $V_{DD}$  rail, transistor **M14** leaves the saturation region and its current drops. This results in a reduction in the bandwidth, and to a second order gain, of first input stage **102**, both of which cause nonlinearity. Accordingly, it is desirable to have transistor **M14** go into a linear mode but still provide the same drain current to input into the differential transistor pair **M0**, **M1**. In other words, it is desirable to "squeeze" the drain-source voltage of transistor **M14**, i.e. to have it work outside of its saturation region, but still provide the same current as before.

[0034] As shown in **FIG. 2**, current source **103** includes PMOS transistors **M15**, **M16**, **M17A**, **M17B**, **M18** and **M57**. Gates of transistors **M17A** and **M17B** are driven by  $V_{IN}$  and  $V_{IP}$ , respectively. The source of transistor **M15** is connected to the supply voltage  $V_{DD}$ , the gate of transistor **M15** is driven by  $V_{B2}$ , and the drain of transistor **M15** is connected to gates of transistors **M16** and **M14**. The drain of transistor **M15** is also connected to a source of transistor **M18**. The drain of transistor **M18** is connected to ground. Transistors **M17A** and **M17B** form a differential pair, and drive NMOS transistor **M19**, and whose tail current source is transistor **M16** (at node **tail1b**). Drains of transistors **M17A**, **M17B** are also connected to a gate of transistor **M18**. A gate of transistor **M57** is connected to  $V_{B1}$ , and the gate of transistor **M15** is driven by  $V_{B2}$ .

[0035] Transistors **M16** and **M14** form a current mirror, such that whatever current flows into **M16** also flows into **M14**. If drain-source voltage  $V_{DS}$  of transistor **M14** is significantly different than  $V_{DS}$  of transistor **M16**, and/or is less than  $V_{GT}$ , then current in the two transistors is no longer well matched. Therefore, two transistors **M17A** and **M17B** are used to remedy the situation. As the input voltages  $V_{IN}$ ,  $V_{IP}$  approach the supply voltage  $V_{DD}$ , and  $V_{DS}$  of transistor **M14** decreases,  $V_{DS}$  of transistor **M16** also decreases. As input



voltages  $V_{IN}$ ,  $V_{IP}$  increase and begin to approach  $V_{DD}$ , the currents in transistors **M16** and **M14** remains the same for higher input voltages compared to without current source **103**.

[0036] Transistor **M15** provides a bias current to transistor **M18**, and can be replaced by an ideal current source, or by a resistor, as long as there is some current flowing.

[0037] Note that to be in a saturation region, transistor **M14** needs to have at least  $V_{GT}$  across the drain to source region (actually, slightly more than  $V_{GT}$ ). In the circuit of **FIG. 2**, transistor **M14** can still operate as a current source, but its drain source voltage  $V_{DS}$  is less than  $V_{GT}$ . This occurs because input transistor **M16** of the current source **103** has the same  $V_{DS}$  as **M14**. The source voltages of **M17A** and **M17B** mimic the source voltages of the input devices, thus matching  $V_{DS14}$  and  $V_{DS16}$  equal. If both  $V_{DS}$  and  $V_{GS}$  of these devices match, the drain currents will be equal as well.

[0038] If transistor **M14** in **FIG. 1** were just a simple tail current source,  $V_{CMI}$  (max) would be similar to the folded cascode topology. As shown in **FIG. 2**, transistors **M14**, **M16** and **M18** make a buffered simple current mirror with transistor **M15** providing the bias for transistor **M18**. What makes current source transistor **M16** squeezable is the two transistors **M17A**, **M17B**, each with a gate connected to each input of first stage **101**. As  $V_{CMI}$  increases and the input differential pair **M0**, **M1** starts to squeeze **M14** and push it into the linear region of operation, transistors **M17A**, **M17B** simultaneously squeeze transistor **M16**, doing the same to it. Because the current flowing out of transistor **M19** does not change, neither can the drain currents of transistors **M16**, **M17A** and **M17B**, so transistor **M16**'s gate voltage, labeled  $V_{B1}$ , adjusts to the appropriate value for the desired drain current in the linear region. Because  $V_{B1}$  also drives the gate of transistor **M14**, the drain current of transistor **M14** is largely unaffected when transistor **M14** leaves the saturation region, unlike the simple current source in the folded-cascode topology. Without the squeezable tail,  $V_{CMI}(\text{max}) = V_{DD} - V_{t0} - V_{GT0} - V_{GT14}$ . With the squeezable tail, the  $V_{GT14}$  term is removed, and  $V_{CMI}(\text{max})$  increases.

[0039] Note that current source 103 may be connected to the gate of M13 of amplifier 102, instead of the gate of transistor M14 of first stage 101. Even without first stage 101, the addition of current source 103 to “squeeze” transistor M13 will be advantageous. (Note that FIGs. 1 and 2 also show length and width dimensions of the various transistors of one exemplary implementation of the present invention.)

[0040] FIG. 4 illustrates the advantages of the present invention in graphical form by illustrating normalized worst-case input stage gain over all worst case process and temperature corners (for  $V_{DD} = 2.5V$ ).

[0041] There is no commonly accepted definition for an op amp’s common mode-input range (CMIR) where high linearity will be obtained. What is usually specified is the minimum and maximum DC voltages which the amplifier can attain. However, signals may be distorted well before these voltages are reached. Over some CMIR, if an amplifier stage’s gain remains constant at the signal frequency of interest, that stage will not contribute to an amplifier’s overall distortion if the signal amplitude stays within the CMIR. FIG. 4 shows the worst case normalized input-stage gain as the common-mode input voltage  $V_{CMI}$  is swept from 0 to 2 V. Normalized gain (meaning the gain at  $V_{CMI} = 1V$  for each curve) was subtracted from the data so that all curves would cross a common point, and the changes in gain as a function of  $V_{CMI}$  could be compared. “Worst-case” here means all combinations (16 total) of NMOS (high and low) transistors and PMOS (high and low) transistors, bias current ( $\pm 20\%$ ) and operating temperature ( $0^\circ C$  and  $125^\circ C$ ) were simulated, and the curves shown in FIG. 4 are ones whose gain changed 1 dB most rapidly from the  $V_{CMI} = 1V$  gain for both increasing and decreasing  $V_{CMI}$ . Each gain was determined in an AC small signal simulation and measured at the maximum NTSC signal frequency of 6 MHz.

[0042] The four curves represent four different amplifier circuits:

[0043] (1) No  $g_m - g_m$  stage 101, amplifier 102 consisting of PMOS differential transistor pair M4-M5, NMOS transistors M8-M9 and current source M13 (in other words, the conventional amplifier 102 alone).

[0044] (2) Input stage PMOS  $g_m$  -  $g_m$  stage **101** with a differential transistor pair **M1-M2**, diodes **M3-M4** and a constant tail current source **M14** is added. In this case, the gate of **M14** is tied to a constant voltage reference and the body connections of the diode are tied to the positive supply.

[0045] (3) Squeezable current source **103**, including transistors **M15-M19**, **M57**, is added to the circuit, compared to the circuit corresponding to the graph of (2).

[0046] (4) The bodies (substrates) of the diodes **M3-M4** are tied to their respective sources, compared to the circuit corresponding to the graph of (3).

[0047] With each successive circuit change, the CMIR over which the gain remains relatively constant increases. This increases the range of  $V_{CM1}$  that a signal may pass with little distortion.

[0048] Thus, the present invention provides an operational amplifier with a first stage that inputs a differential input signal and absorbing common mode variations in the differential input signal, and that outputs a first differential signal. The input stage includes a differential transistor pair receiving the first differential signal from the first stage. An output stage is connected to the input stage and outputs an amplified signal corresponding to the first differential signal.

[0049] The list below shows exemplary dimensions of one embodiment of the present invention:

[0050] **M0** characteristics:  $w$  (width) = 10  $\mu\text{m}$ ,  $l$  (length) = 0.24  $\mu\text{m}$ ,  $m$  (multiplicity) = 12

**M1** characteristics:  $w$  = 10  $\mu\text{m}$ ,  $l$  = 0.24  $\mu\text{m}$ ,  $m$  = 48

**M2** characteristics:  $w$  = 10  $\mu\text{m}$ ,  $l$  = 0.24  $\mu\text{m}$ ,  $m$  = 12

**M3** characteristics:  $w$  = 10  $\mu\text{m}$ ,  $l$  = 0.24  $\mu\text{m}$ ,  $m$  = 12

**M4** characteristics:  $w$  = 10  $\mu\text{m}$ ,  $l$  = 0.24  $\mu\text{m}$ ,  $m$  = 12

**M5** characteristics:  $w$  = 10  $\mu\text{m}$ ,  $l$  = 0.24  $\mu\text{m}$ ,  $m$  = 12

**M8** characteristics:  $w$  = 10  $\mu\text{m}$ ,  $l$  = 0.4  $\mu\text{m}$ ,  $m$  = 32

**M9** characteristics:  $w$  = 10  $\mu\text{m}$ ,  $l$  = 0.4  $\mu\text{m}$ ,  $m$  = 32

**M10** characteristics:  $w$  = 10  $\mu\text{m}$ ,  $l$  = 0.24  $\mu\text{m}$ ,  $m$  = 16

**M11** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 0.24\ \mu\text{m}$ ,  $m = 80$

**M12** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 0.48\ \mu\text{m}$ ,  $m = 80$

**M13** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 0.5\ \mu\text{m}$ ,  $m = 60$

**M14** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 0.24\ \mu\text{m}$ ,  $m = 64$

**M15** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 0.6\ \mu\text{m}$ ,  $m = 10$

**M16** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 0.24\ \mu\text{m}$ ,  $m = 15$

**M17A** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 0.24\ \mu\text{m}$ ,  $m = 12$

**M17B** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 0.24\ \mu\text{m}$ ,  $m = 12$

**M18** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 0.24\ \mu\text{m}$ ,  $m = 20$

**M19** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 1\ \mu\text{m}$ ,  $m = 16$

**M57** characteristics:  $w = 10\ \mu\text{m}$ ,  $l = 2\ \mu\text{m}$ ,  $m = 33$

**[0051]** It will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined in the appended claims. Thus, the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.